Comparative life cycle assessment of standard, cellulose-reinforced and end of life tires fiber-reinforced hot mix asphalt mixtures

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Abstract

A change in the current waste management practices is needed to improve the reuse and recycling rates and limit the increasing environmental impacts (EI) on the environment. The construction sector is one of the major contributors to the global EI, regarding energy consumption, emissions released into the atmosphere and extracted natural resources. In this context, the reuse of waste and scraps from other sectors/production chains (i.e. fibers from end of life tires – ELT) in road pavements potentially represents a best practice.

This study presents a comparative life cycle assessment (LCA) among three different typologies of hot mix asphalt mixtures (HMA): standard, cellulose-reinforced and ELT fiber-reinforced. The study focuses on the environmental analysis of the realization and maintenance of 1 m^2 of HMA mixtures for a motorway road, during a time lapse of 30 years. The life cycle inventory includes primary data, collected from different industrial companies and from laboratory test, secondary data, derived from the GaBi professional database 2016. The service lives of the different typologies of HMA have been evaluated through a laboratory study and a full-scale application in a trial section located in an important Italian motorway. The porous asphalt mixture containing ELT fibers showed about 70% increase in the fatigue resistance with respect to the porous asphalt mixture containing cellulose fibers. The environmental impacts have been quantified in terms of Cumulative Energy Demand (CED), Global Warming Potential (GWP), and ReCiPe midpoint and endpoint indicators.

The obtained results show that raw materials (particularly bitumen) are the most impactful flows for all the three considered mixtures and for all the impact categories. Also the transportation phases contribute with relevant impacts, while energy flows consumed during the HMA preparation and laying are almost negligible. Considering the CED, GWP and ReCiPe endpoint indicators, the ELT fiber-reinforced HMA resulted the best alternative (reduction of 25% in comparison with the standard HMA), followed by the cellulose-reinforced HMA (-10%), thanks to the higher service life. For some ReCiPe midpoint categories (Agricultural land occupation, Freshwater ecotoxicity, Freshwater eutrophication, Marine eutrophication and Terrestrial ecotoxicity), instead, the worst scenario is the cellulose HMA, due to the high contribution of the cellulose material.

Keywords: hot mix asphalt mixtures, life cycle assessment, end-of-life tires fiber, cellulose fiber.

Abbreviations:

HMA: Hot mixture asphalt

ELT: End of life tires

LCA: Life cycle assessment

SMA: Stone mastic asphalt

LCI: Life cycle inventory

LCIA: Life cycle impact assessment

GPP: Green public procurement

FU: Functional unit

EoL: End of life

RAP: Reclaimed asphalt pavement

CED: Cumulative energy demand

1. Introduction

The construction sector is one of the major contributors to the environmental impact (EI), regarding energy and water consumption, emissions released into the atmosphere and extracted natural resources. According to Park et al. (2003), construction involves manipulation and use of large quantities of natural and man-made materials. Moreover, the construction and operation of infrastructures involve large quantities of energy. As a consequence, the wide variety of materials used in construction work, as well as fuel and electricity used by machinery and recycling plants produce a significant EI. Thus, it is essential to promote sustainability concepts in construction, with the aim to reduce the ecological footprint during the whole life cycle of a structure.

Focusing on the road pavement sector, about 325 million tons of hot mix asphalt (HMA) are consumed each year at European level (EAPA, 2017), of which about 22 million tons in Italy (SITEB, 2018). Expanding and maintaining the road pavement network is a resource-intensive process, which annually involves about 150 billion dollars and 350 million tons of raw materials for the construction, rehabilitation, and maintenance of the European road system (Holtz et al., 2000; Federal Highway Administration, 2006, 2007). Currently, the challenge is to meet this increasing demand by using environmentally sustainable materials and engineering practices.

Recently, several literature studies have proved that through the use of reinforced HMA mixtures it is possible to increase the physical and mechanical properties of a road pavement, with a consequent increase of its lifetime. The study and development of new processes and the use of innovative materials also contribute to limit the environmental impacts caused by HMA-based pavements in the entire life cycle, through the reduction of the consumption of energy, virgin aggregates and bitumen, as well as the quantity of disposed reclaimed asphalt from pavement demolition (González et al., 2018; Santos et al., 2018; Arteaga et al., 2019). In addition, from the socio-economic point of view, the increase of the HMA service life contributes to further improve the safety and to decrease the demand for new road infrastructures (Peyman et al., 2016).

In this context, the present paper aims to investigate the environmental sustainability of reinforced HMAs prepared by adding fibrous materials derived from the dismantling of end-of-life tires (ELTs). This study is part of the European project REFIBRE, started in 2014, with the objective to evaluate the possibility to reuse ELT fibers not only in special mixtures where fibers are typically included to avoid bitumen drain down (porous asphalt mixtures and stone mastic asphalt (SMA) mixtures), but also in the lower layers of road pavements (i.e. binder and base), in order to increase the fatigue properties of the mixes. This initiative potentially contributes to mitigate the environmental issues related to solid wastes (Wilson et al., 2015), of which a relevant percentage (about 70%) is not reused nor recycled, with an enormous loss of money and precious resources (Tisserant et al., 2017). Specifically, the management and reuse of solid wastes derived from ELTs, which represent a relevant quantity in Europe (European Commission, 2000), is investigated.

Several research studies have been focused in the use of ELT fibers for different applications as reinforcement material. Some authors evaluated the influence of waste tire fibers on the strength and stiffness of concrete (Flores Medina et al., 2017; Sofi et al., 2017; Sousa et al., 2017), other ones like filler material in cement stabilized clays (Yadaw and Tiwari, 2017) or as building insulation panels (Van de Lindt et al., 2008). Landi et al. (2016, 2018a) compared the environmental sustainability of different second life applications and end of life scenarios of ELT fibers. However, currently about 100% of ELT waste flows are recovered in several European countries, but only half of them are used as secondary materials in other applications (EASME, 2015; ETRMA, 2015).

This paper wants to integrate the above-mentioned state of the art by evaluating the environmental performance of the ELT fiber-reinforced HMA and comparing it against a standard HMA and a cellulose-reinforced HMA. To carry out this study, at first, the mechanical and fatigue performances of the three different HMA mixtures were assessed. Both a laboratory study and a full-scale application in a trial section of an Italian motorway were tested to estimate with acceptable reliability the service lives of the three layers (base, binder and wearing course) for the three considered mixes. Then, the Life Cycle Assessment (LCA) methodology has been used to quantify the environmental load in terms of different impact categories (Cumulative Energy Demand, Global Warming Potential, ReCiPe Midpoint and Endpoint), with the aim to establish the most sustainable solution and to identify opportunities to further reduce the impacts.

The paper is organized as follows. Section 2 describes the physical and mechanical properties of the different types of HMA mixtures considered in this analysis. Section 3 presents the goal and scope of the LCA study, together with the inventory data. Section 4 presents and discusses the obtained results. Finally, Section 5 reports conclusions and some proposals for correlated future work.

2. Material

The use of fibers in HMA has been proposed in the early 1960s as a solution to avoid the bitumen drain down (i.e. flowing of bitumen to the bottom of the truck during HMA hauling) in the mixtures characterized by a high content of binder (Serfass and Samanos, 1996). In the following years, this technique has consolidated, and the presence of fibers is currently required in porous asphalt mixtures and SMA mixtures. Fibers of different nature can be used for this purpose, including cellulose, asbestos, rock wool, glass wool, polyester. The fiber content depends on the type and the thread dimensions, and typically varies in the range 0,20÷0,30% by aggregate weight (Sayyed et al., 2010). Recently, some authors (Mahrez et al., 2003; Park et al., 2015) proposed the use of fibers in HMA as reinforcing materials, with the aim to provide additional tensile strength and increase the amount of strain energy that can be absorbed during the fatigue and fracture process of the mix. However, this practice has not significantly widespread, mainly because of economic issues.

The investigation involved a laboratory study and a full-scale application in a trial section located in an important Italian motorway. Tests have been carried out both on laboratory-prepared specimens and on cores taken from the trial section, with the objective to compare the mechanical and performance properties of different HMA containing no fiber (reference mix), cellulose fibers and ELT fibers.

In particular, the phenomenon of drain down has been observed on laboratory-prepared porous asphalt mixtures including the same amount of bitumen (5% by mix weight) and cellulose fibers/ELT fibers/no fibers. The loose mixtures (approximately 500 g) were put in different glasses and kept in the oven at 180 °C for 1 hour. Then the mixtures were removed from the glasses and the amount of bitumen drained on the bottom of the recipients was observed and weighted. Results showed that ELT fibers allow obtaining an excellent performance in reducing the risk of bitumen drain down in porous asphalt mixtures (Figure 1). In particular, the beneficial effect is even higher than in the case of using cellulose fibers. This is probably related to the presence of small rubber particles in ELT fibers, which reacts with the oily component of bitumen increasing its consistency.

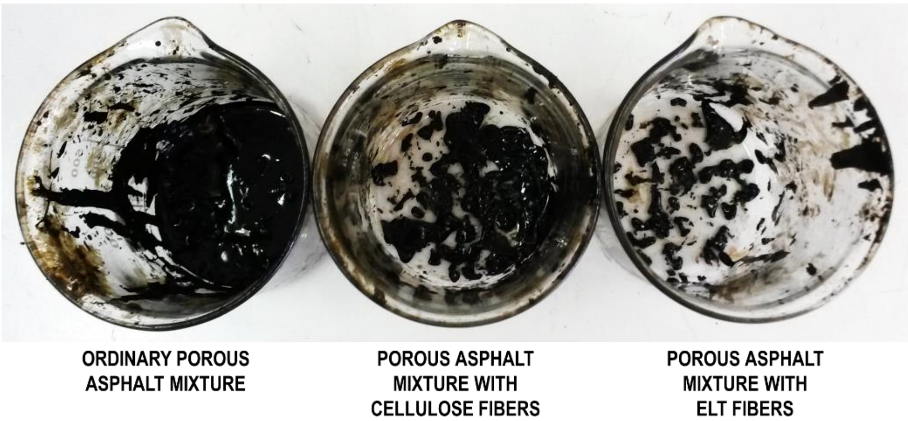


Figure 1: Effect of the fibers in reducing bitumen drain down from porous asphalt mixtures

The resistance to cyclic loads was measured in laboratory on HMAs for wearing and binder layers. Tests were carried out on laboratory-prepared specimens (binder mixture) and on the cores taken from the trial section (binder, SMA and porous asphalt mixtures), appropriately cut to obtain suitable specimen dimensions (cylinders with 100 mm diameter and approximately 40 mm height). A servopneumatic machine was used to determine the fatigue resistance of the mixtures in indirect tensile configuration, according to the EN 12697-24 Annex E standard. During the test, pulse loads with 0,1 s loading time and 0,4 s rest time were applied on the vertical diametral plane. This loading results in repeated tensile stress pulses perpendicular to the direction of the applied load which cause the specimen to fail by splitting along the central part of the vertical diameter. The measurement protocol included a test temperature of 25 °C, 3 stress levels (variable between 100 kPa and 350 kPa in order to obtain cycles at failure between 100 and 100000 for each mixture) and at least 3 test repetitions for each loading condition. The fatigue failure of the specimen N_f was assumed in correspondence to the number of load applications when the sample broke and the vertical crack completely separated it into two halves. Results proved that HMA including ELT fibers have a noticeably high resistance to fatigue. Figure 2 shows the fatigue curves, which relate the tensile stress on the HMA cylindrical specimens as a function of the number of cycles at failure, for the different mixtures. The graphs highlight that the binder mixtures containing ELT fibers have a resistance to repeated load that is approximately one order of magnitude higher than the reference HMA with no fibers, under the same conditions. This can be observed from the tests on laboratory-produced specimens and on the cores taken in the road pavement trial section. The improvement of performance is probably due to the ability of the fibers in sewing the micro-crack edges together and thus opposing the micro-crack evolution into a macro-crack. It has to be remarked that the binder layer, within the pavement structure, has the specific function to withstand the repeated loads induced by traffic (in cooperation with the base layer), differently from wearing layer that basically has surface properties (regularity and adhesion with tires). Thus, this result denotes the significant contribution of the ELT fibers in extending the service life of the pavement (likely twice) and delaying the formation of fatigue-related distresses. Also, in the case of SMA mixtures the presence of ELT fibers determines a relevant increase in the fatigue performance (+30%), but lower than for binder mixtures. In this case, the real contribution of ELT fibers was not fully visible because of the high air voids content of the cores that determined a noticeable data scattering.

Benefits related to the use of ELT fibers are important even if compared with cellulose fibers; in fact, the porous asphalt mixture containing ELT fibers showed about 70% increase in the fatigue resistance with respect to the porous asphalt mixture containing cellulose fibers. This is probably an effect of the higher ability of ELT fibers in avoiding bitumen drain down, resulting in a higher thickness of the bitumen film that coats the aggregate particles.

In conclusion, the presented findings proved that the presence of ELT fibers leads to a significant increase of the fatigue resistance of the HMA, both with respect to the mixtures without fibers (+300% on lab-produced binder mix, ×10 times on binder-layer cores, +30% on SMA cores) and with cellulose fibers (+70% on porous asphalt cores). For the LCA purpose, a general increase in the service life of the HMA mixtures equal to 50% can be considered representative.

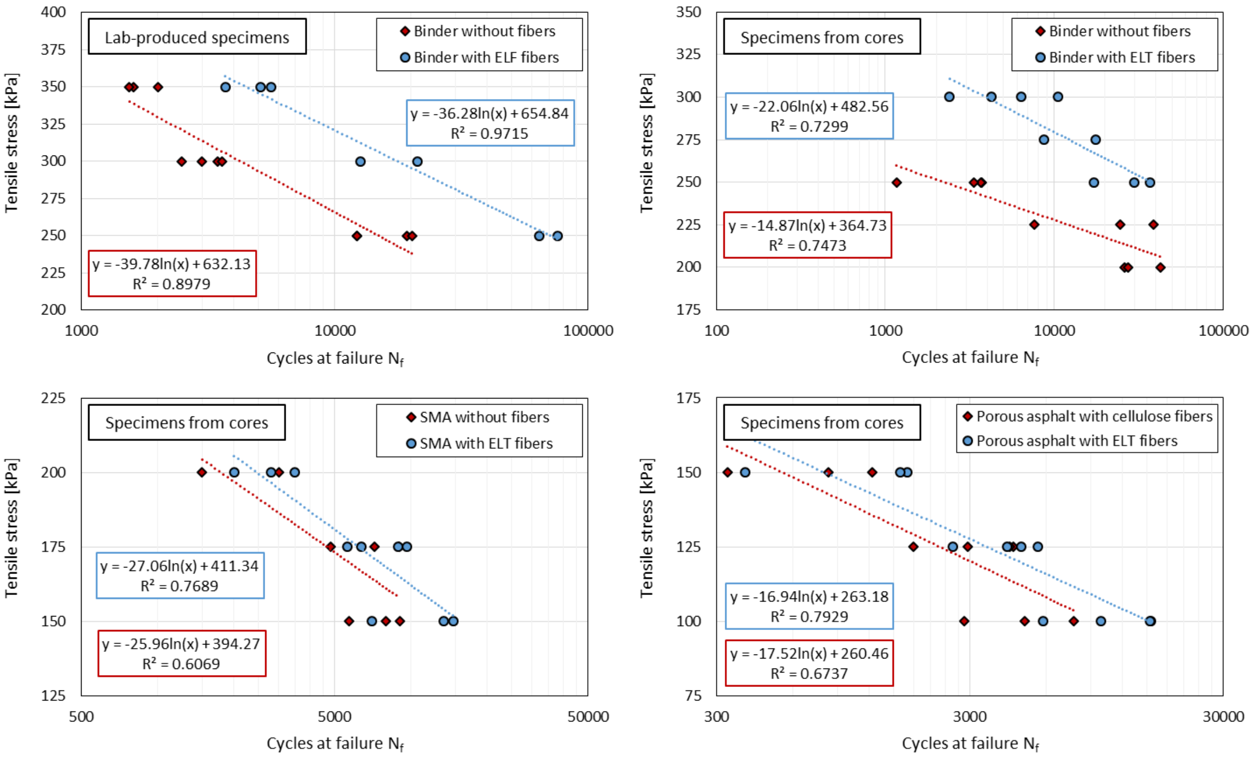


Figure 2: Results from fatigue tests for binder mix (lab-produced specimens and cores), SMA and porous asphalt mixtures

3. Methods

This study has been carried by following the Life Cycle Assessment methodology (ISO 14040-14044) that allows to analysing a product, process, service or activity over its entire life cycle and to quantify the relative impacts on the environment. According to the above-mentioned standards, the LCA studies must include four phases:

- Goal and scope definition: during this phase, the objectives of the analysis need to be clarified, the considered functional unit must be univocally defined, and the spatial and temporal system boundaries must be identified;
- Life cycle inventory (LCI): this is a key phase of an LCA study in which the system under analysis is subdivided in unitary processes. Successively, for each identified process, an input-output analysis needs to be conducted to collect and classify all the relevant flows;
- Life cycle impact assessment (LCIA): during this phase the input-output flows are translated in midpoint and/or endpoint impact categories through the application of an impact assessment methodology, based on characterization and/or weighting factors;
- Results interpretation: the last phase foresees the analysis, critical review and interpretation of the obtained results, as well as the definition of possible improvement strategies.

The following subsections describe the full details about the goal and scope definition and the LCI phases, while results and successive discussion are reported in the following section 4.

3.1 Goal and Functional unit

The goal of this study is to evaluate and compare the environmental loads of three different HMA mixtures: (i) standard, (ii) reinforced with cellulose fibers, and (iii) reinforced with fibers derived from ELT. More specifically, the LCA study aims to compare the three scenarios and establish which is the most environmentally friendly one in a life cycle perspective. The results should be mainly of interest for managing bodies of road infrastructures as a support for the decision-making toward the improvement of road environmental performance. In addition, this comparative study can support public authorities in the context of green public procurement (GPP) activities.

According to the ISO standards, the functional unit (FU) can be defined as an equivalent amount of product function that represents a reference unit useful to compare different systems. In this study the FU is defined as "the realization and maintenance of 1 m^2 of HMA mixture for a motorway road, composed of three layers (base, binder, wearing course), during a time lapse of 30 years". Such time lapse has been chosen since it represents the maximum value of service life for the considered layers and HMA mixture typologies (in particular it refers to the duration of the base layer in case of ELT reinforced asphalt mixture).

The road characteristics considered in the analysis refer to the Italian motorway where the trial section was built. In particular, the road is composed of two independent carriageways including 3 lanes in each direction (2 lanes for the vehicle traffic and 1 emergency lane) and separated by a median barrier. The width of the pavement is 15 m and the total depth is 26 cm. The three pavement layers have the following characteristics:

- Base: it is the lower layer of the pavement with a thickness of 15 cm and an average density of 2350 kg/m^3;

- Binder: it is the intermediate layer of the pavement with a thickness of 6 cm and an average density of 2350 kg/m^3;
- Wearing course: it is the upper layer of the pavement with a thickness of 5 cm and an average density of 2400 kg/m^3.

3.2 System description and boundaries

The present study can be classified as a cradle to gate analysis, since it includes all the phases from the extraction of raw materials to the pavement construction and maintenance during the time lapse specified in the FU (i.e. 30 years). As in other similar studies, pavement use and End of Life (EoL) are not considered in the analysis, as well as subgrades, embankments, drainages and road marking (Santero et al., 2011a, 2011b; Giani et al., 2015).

The following Figure 3 reports a flowchart of the unit processes considered in the HMA pavement construction and maintenance for the three scenarios, as well as details about the system boundaries.

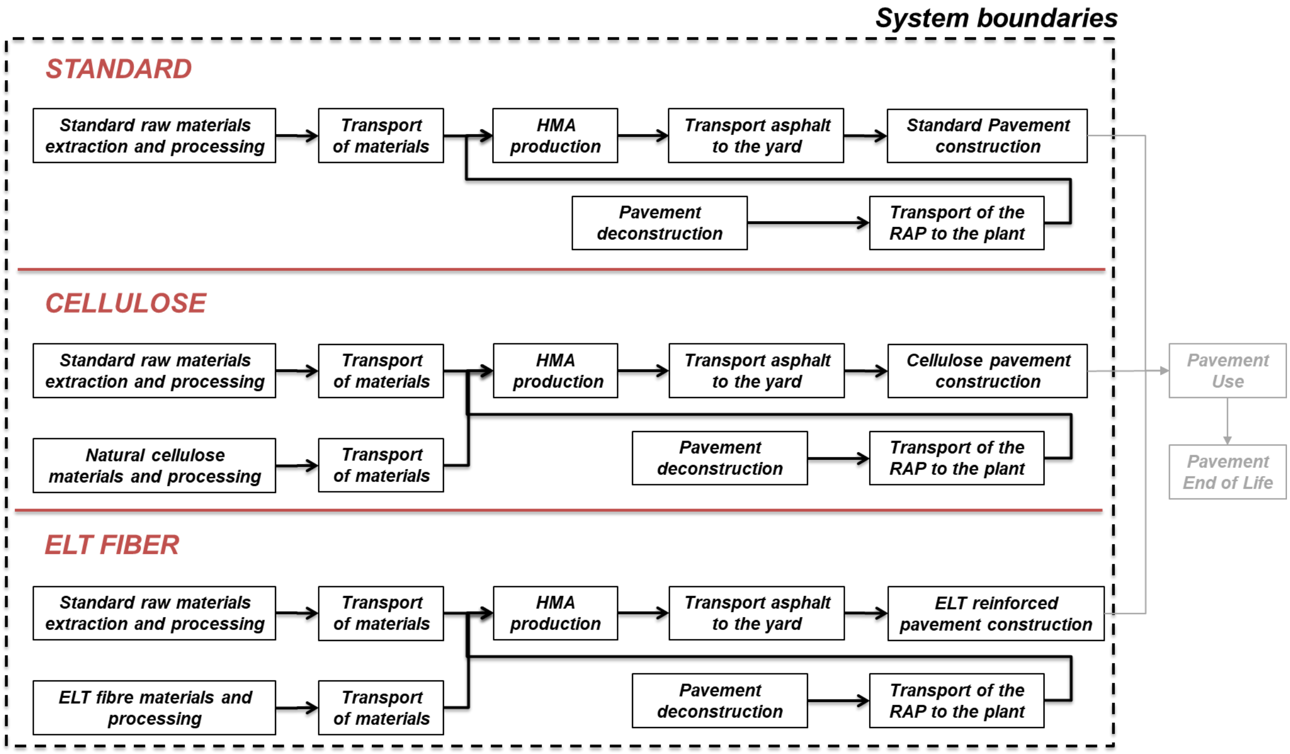


Figure 3: Details of each scenario and system boundaries

The process begins with the extraction and processing of standard raw materials (e.g. limestone, bitumen) that are successively transported to the HMA production plant. Concurrently, in the case of reinforced HMA mixtures, the cellulose and the ELT fibers must be supplied to the plant. Regarding the latter, the considered production process, presented in previous studies of the same authors (Landi et al., 2018a, 2018b), includes the following phases: (i) Grinding of ELT; (ii) Magnetic separation of steel wires; (iii) Granulation of residual rubber; (iv) Pulverization of rubber; (v) Separation of rubber powder and dirty fibers; (vi) Fiber cleaning; (vii) Fiber compaction and pellet production. As also stated in previous studies, realistic scenarios of HMA pavement realization must include the use of reclaimed asphalt pavement (RAP), together with the standard raw materials (Giani et al., 2015). RAP could derive from the same road construction site or from other ones by means of specific milling machines. In any case, the RAP has to be provided and transported to the HMA production site.

At the HMA production site, the input raw materials are mixed together through a mixing machine and following specific recipes. Since the object of the study is on HMA, during this phase it is also necessary to heat the mixture at a temperature in the range 150-200 °C in order to ensure the fluidity of the bitumen (Peinado et al., 2011). Finally, the HMA mixture is transported to the road construction site, laid by means of finishing machines, and compacted through roller machines.

As it is possible to see from Figure 3, there are no essential differences in terms of unit processes, among the three considered HMA typologies. Rather, the main differences are related to recipes and, as a consequence, resource consumption in the different production steps, as detailed in the next section about the LCI.

3.3 Life cycle inventory (LCI)

Both primary and secondary data, coming from the GaBi professional database 2016 (thinkstep, 2016), have been used to carry out the different analyses of this study. The following assumptions have been made during the data collection phase:

- Data related to the different HMA mixtures recipes have been collected by measuring the quantities of raw materials used during the HMA production phase;
- Data related to resources consumed during the HMA production phase have been collected by measuring the consumption of equipment;
- Data related to energy consumption of the HMA laying and compaction have been estimated in collaboration with the involved companies;
- Data related to the ELT fiber treatment derives from previous studies of the same authors, who associated no impacts to the recovered raw material (i.e. dirty fiber from ELT) and calculated the impacts due to the fiber cleaning and preparation to reuse (Landi et al., 2018a, 2018b);
- Inventory data related to input raw materials and cellulose production have been derived from the GaBi professional database 2016;
- Inventory data related to electric energy generation and other resources (e.g. natural gas) have been derived from the GaBi professional database 2016. Comparing such data with recent literature studies (Cucchiella et al., 2017), they can be still considered valid and sufficiently reliable;
- Distances for all the transport phases (e.g. raw material supply, transportation from HMA production site to road construction site) have been estimated on the basis of interviews of key managers of the involved companies;
- Inventory data related to transportation have been derived from the GaBi professional database 2016. In particular, Euro 5 diesel trucks have been chosen for all the transport phases (Giannouli et al., 2007);
- No impacts have been associated to RAP, except those derived from pavement deconstruction and RAP transportation;
- Due to the unavailability of data, no direct and indirect emissions to air at both the HMA production plant and the yard have been considered in the study. However, this assumption should not heavily influence the final results since previous studies confirmed that emissions to air produce negligible or very few contributions to the total environmental impact of HMA mixtures (Vidal et al., 2013; Giani et al., 2015; Farina et al., 2017);

- Manufacturing of the equipment used for the HMA production, laying and compaction are considered out of scope of the present study, since the total quantities of HMA mixtures treated by this machine during their service lives is much larger than the quantity considered in the functional unit (1 m^2 of HMA per 30 years). As a consequence, the equipment contributes with negligible impacts, as demonstrated in other LCA studies focused on production plants (Favi et al., 2016).

The following subsections report details about the inventory data used in the present study.

Input raw materials

The materials used to prepare asphalt mixtures are essentially aggregates and bitumen. As previously anticipated, also RAP is commonly used in partial substitution of virgin aggregates (generally 10÷30% in weight) (EAPA and NAPA, 2011; Giani et al., 2015)). The recipes considered in this study include a measured percentage of 18% of RAP.

The following Table 1, report the full details about the inventory data related to input raw materials. The density value for the granular materials have been measured in laboratory according to the EN 1097-6 standard, while the bitumen density has been provided by the supplier. The same value of bitumen density is confirmed in a recent scientific literature study (Ghaderi et al., 2019).

Table 1: Input raw materials used for producing standard, cellulose fiber and ELT fiber HMA mixtures.

Material	**Density [kg/m^3]**	**Quantity [%]**			**Total mass per 1m^2 for a service life of 30 years [kg]**
		Base (15 cm)	**Binder (6 cm)**	**Wearing course (5 cm)**	
Standard HMA mixture					
Limestone12/20	2000	16	16	32,3	240,7
Limestone 8/16	2500	30	30	32,3	442,6
RAP	2200	17,9	15	-	148,0
Sand 0/4	1700	30,3	32	23,3	281,9
Filler	2800	1,8	2	6,1	50,8
Bitumen	1010	4	5	6	38,3
Cellulose reinforced HMA mixture					
Limestone12/20	2000	16	16	32,3	207,3
Limestone 8/16	2500	30	30	32,3	379,9
RAP	2200	17,9	15	-	126,3
Sand 0/4	1700	30	31,7	23	238,9
Filler	2800	1,8	2	6,1	43,8
Bitumen	1010	4	5	6	24,3
Cellulose	350	0,3	0,3	0,3	3,0

ELT fiber reinforced HMA mixture					
Limestone12/20	2000	16	16	32,3	166,6
Limestone 8/16	2500	30	30	32,3	305,7
RAP	2200	17,9	15	-	101,4
Sand 0/4	1700	30	31,7	23	192,6
Filler	2800	1,8	2	6,1	35,2
Bitumen	1010	4	5	6	19,6
ELT fiber	350	0,3	0,3	0,3	2,5

Energy and resource consumption

The production of HMA includes the mixing of input raw materials and their heating through the use of specific machines that consume electric energy and natural gas. All these flows have been measured at the production site of the involved company, by means of a power meter and a gas meter. The following Table 2 reports the full details about the inventory data related to the HMA production phase for the three typologies of mixtures. It can be observed that the use of reinforcements leads to a reduction of processing time and, as a consequence, of resource consumption. In particular, ELT fiber HMA production requires about 50% of electricity and natural gas in comparison with standard HMA. Such reductions are essentially due to the higher service lives of reinforced HMA mixtures that involve the use of less quantities of input raw materials (as reported in Table 1) to be mixed during the period considered in the FU (i.e. 30 years).

Table 2: Resource consumed for producing of 1 m^2 of HMA mixture for 30 years of service life

	Standard HMA	**Cellulose HMA**	**ELT fiber HMA**
Electricity [kWh]	1,051	0,901	0,579
Natural gas [kg]	7,185	6,153	4,951

Regarding the deconstruction of the old pavement and the laying and finishing of the new HMA, the considered data are relative to the consumption of the used machines. These quantities have been estimated on the basis of the average hourly fuel consumptions and processing times required to mill and rebuild 1 m^2 of HMA. The following Table 3 reports the diesel consumption estimated for each machine. As for the HMA production phase, considering the different service lives for the three mixtures, the number of required laying in 30 years is minor in case of reinforced HMAs,, thus minor quantities of fuels are consumed.

Table 3: Diesel consumption of each machine used for the deconstruction, laying and finishing phases of 1 m^2 of HMA for 30 years of service life.

	Standard HMA	Cellulose HMA	ELT fiber HMA
Milling machine [l]	0,614	0,525	0,423
Finishing machine [l]	0,262	0,225	0,183
Roller [l]	0,019	0,016	0,013

Transportation data

Data about transportation of raw materials, RAP and HMA mixtures have been set according to the indications provided by key managers of the involved company. They have been estimated considering average distances between the supplier site, the production site and the road construction site. The following Table 4 reports the full details about the inventory data related to transportation.

Table 4: Transportation data

	Freight	Distance [km]	Vehicle type (ton)
Transportation to the HMA production plant	Limestone 12/20	150	Truck 16-32
	Limestone 8/16	150	Truck 16-32
	RAP	50	Truck 16-32
	Sand 0/4	100	Truck 16-32
	Filler	100	Truck 16-32
	Bitumen	100	Truck 16-32
	Cellulose / ELT fiber	50	Truck 16-32
Transportation to the yard	HMA	50	Truck 16-32

Road pavement service life and maintenance

The service life of any product can be defined as the period of time in which the product maintains its full functionalities. This value can be generally established on the basis of specific normative, maintenance plans or market surveys. In case of road pavements, the estimation of the service life is even more complex since other essential factors need to be considered, as the weather conditions, the typology of the road, the traffic flows, the availability of economic resources to renovate the HMA in case of public roads, etc. Therefore, no univocal values for service lives of road pavements and layers can be found in normative or literature studies (Santero et al., 2011a).

For this reason, average values of service life related to commonly used asphalt mixtures (i.e. standard and reinforced with cellulose) have been established on the basis of indications provided by different companies involved in the HMA production and road construction, and by public and private managing bodies of road infrastructures. Regarding the innovative asphalt mixture reinforced with ELT fibers, instead, the service life of each layer has been set by considering an increase of about 50% in comparison with the standard HMA, as demonstrated through the fatigue tests presented in Section 2. The following Table 5 reports full details about the service lives considered in the present LCA study.

Table 5: Service lives of the different layers and HMA mixture typologies

	Standard HMA	**Cellulose HMA**	**ELT fiber HMA**
Base [year]	20	23	30
Binder [year]	10	12	14
Wearing course [year]	7	8	10

3.4 Life cycle impact assessment (LCIA) methods

As in any LCA study, also the environmental impacts of HMA mixtures can be quantified by using a large variety of environmental metrics, calculated on the basis of different impact assessment methods. However, analyzing the LCA studies focused on this sector, energy indicators seem the most widespread and common metrics (Santero et al., 2011a). For this reason, the first chosen indicator is the Cumulative Energy Demand (CED) method, which is a measure of the direct and indirect energy consumption over the whole product life cycle (expressed in [MJ]), based on the energy harvested approach (Frischknecht et al., 2015).

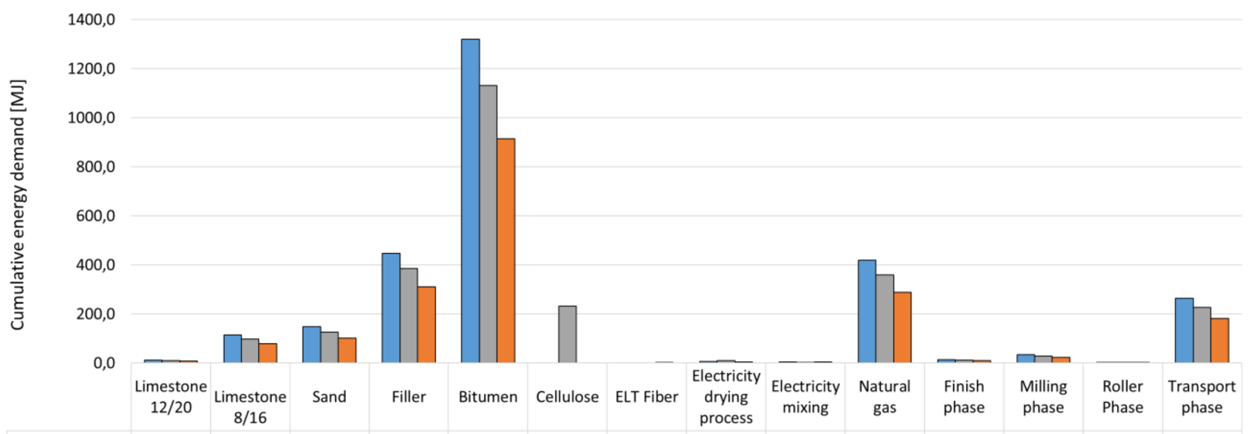
Another very common environmental metric in the context of LCA of HMA pavements is certainly the emissions of Green House Gas (GHG) in the atmosphere that contribute to global warming and climate changes (Giani et al., 2015). The Global Warming Potential (GWP) indicator has been used to calculate the quantity of carbon dioxide equivalents (expressed in [kg CO_2 eq]) deriving from CO_2 and non-CO_2 gases in a time horizon of 100 years. In particular, the impact assessment method described in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has been adopted (IPCC, 2007).

However, the construction and maintenance of a HMA pavement over its life cycle involve different typologies of impacts (e.g. land consumption, depletion of fossil resources, acidification of soils, eutrophication of water, human toxicity) (Giani et al., 2015). Therefore, other impact categories need to be considered in order to have a more comprehensive view on the potential environmental damages. This is the reason why the ReCiPe 2008 LCIA method has been used (Goedkoop et al., 2009). At midpoint level, this method allows to assessing 18 different impact categories (e.g. fossil depletion [kg oil eq], terrestrial acidification [kg SO_2 eq], ozone depletion [kg CFC-11 eq], freshwater ecotoxicity [kg 1,4-DB eq]) which can be grouped and weighed to obtain 3 endpoint damage categories (human health [DALY], ecosystem quality [species.yr], resources[$]) and, finally, a single score (expressed in [EcoPt]), after a normalization and another weighing. Regarding midpoints, the weighting set chosen in this study is the Hierarchist (H) perspective that is considered more balanced than the other two alternatives. Regarding endpoints, instead, the Average (A) weighting set has been used, while the used normalization factor is relative to the impact generated by an average European citizen in the year 2000.

4. Results and Discussion

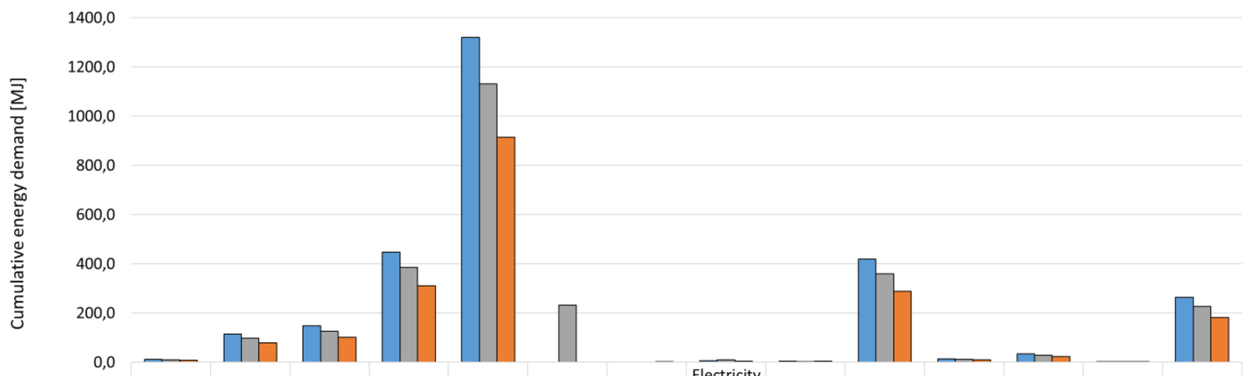
Life cycle impact assessment calculated by using the life cycle inventory data and the specific environmental impact categories described above is shown in this section. The LCA results highlight several interesting aspects of the environmental performance associated with each of the three considered HMA mixtures, used for the construction and maintenance of 1m^2 of highway road in a period of 30 years (as specified in the chosen FU).

4.1 Cumulative Energy Demand



	Limestone 12/20	Limestone 8/16	Sand	Filler	Bitumen	Cellulose	ELT Fiber	Electricity drying process	Electricity mixing	Natural gas	Finish phase	Milling phase	Roller Phase	Transport phase
Standard HMA	11,3	114,0	147,9	447,0	1319,4			6,7	5,3	420,0	14,4	33,8	1,0	264,5
Cellulose HMA	9,7	97,9	125,4	385,8	1132,1	233,2		10,2	2,4	359,5	12,4	28,9	0,9	226,4
ELT HMA	7,8	78,8	101,1	310,2	914,1		2,2	4,6	3,6	289,4	10,1	23,3	0,7	182,4

Figure 4 presents the results obtained with the environmental assessment for the three evaluated scenarios in terms of CED. The main contribution is relative to the production and consumption of the bitumen, which represents about 45% of the total impact for all scenarios considered. Bitumen is an essential "ingredient" of the HMA mixtures, mainly used as an adhesive to bind the other materials together. For this contribution, a saving of about 187 MJ and 405 MJ can be obtained by switching from the standard HMA to the cellulose and ELT fiber HMAs, respectively. This is a direct consequence of the lower quantities of bitumen (and also other input raw materials) needed in the life cycle of reinforced HMAs.



	Limestone 12/20	Limestone 8/16	Sand	Filler	Bitumen	Cellulose	ELT Fiber	Electricity drying process	Electricity mixing	Natural gas	Finish phase	Milling phase	Roller Phase	Transport phase
Standard HMA	11,3	114,0	147,9	447,0	1319,4			6,7	5,3	420,0	14,4	33,8	1,0	264,5
Cellulose HMA	9,7	97,9	125,4	385,8	1132,1	233,2		10,2	2,4	359,5	12,4	28,9	0,9	226,4
ELT HMA	7,8	78,8	101,1	310,2	914,1		2,2	4,6	3,6	289,4	10,1	23,3	0,7	182,4

Standard HMA   Cellulose HMA   ELT HMA

Figure 4: LCIA in terms of characterized Cumulative Energy Demand (CED)

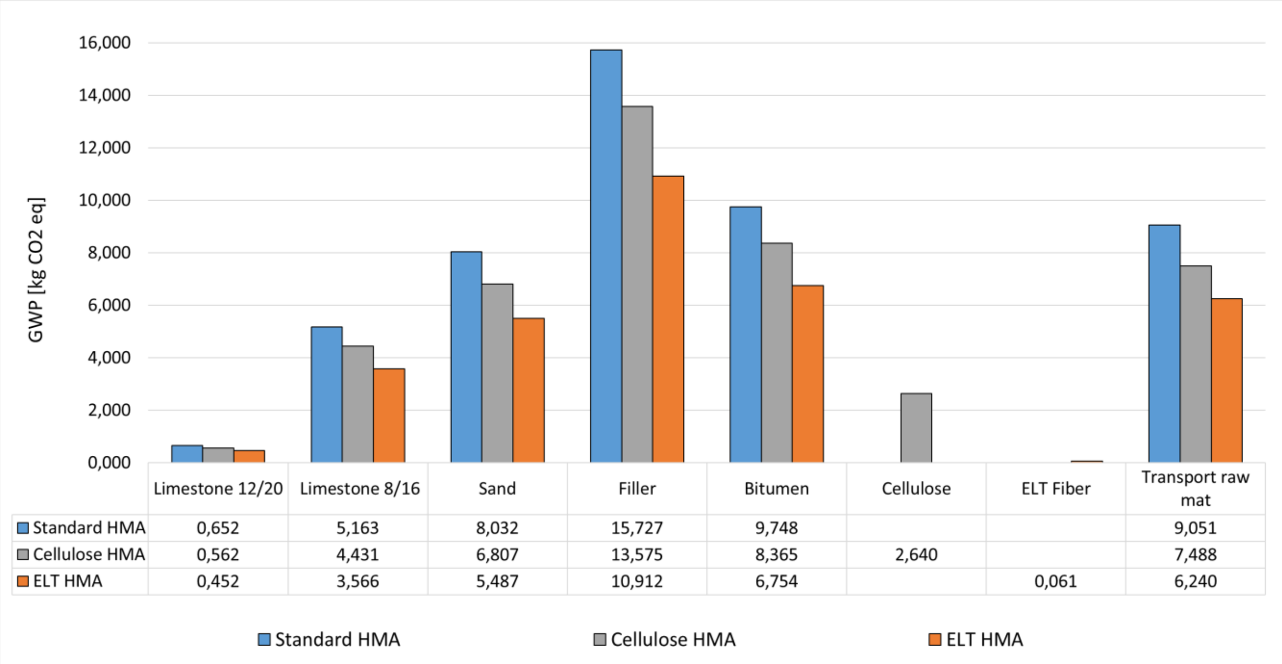
Splitting the contribution of each phase, as for the LCI analysis, the following general results can be calculated: the raw material extraction and processing contribute with the higher impacts (about 75 % of the total), followed by the HMA production with about 15 % and the transports with almost 10 %, while the yard operations (deconstruction, laying and finishing phases) produce negligible impacts compared to the other flows/processes. Considering the cellulose HMA, a relevant contribution of 8,9 % is due to the cellulose production. Even if the total quantity used for the considered life cycle of 30 years is only 3 kg, the high unitary environmental impact of the cellulose material in terms of CED (77,7 MJ/kg) makes the cellulose impacts quite critical. Considering the ELT fiber HMA, instead, the contribution of the ELT fiber material is negligible since its impact derives only from the processes needed to prepare this material for reuse, while no impacts have been associated to the raw material derived from a waste of another sector (Landi et al., 2018a, 2018b).

Summarizing, the estimated saving in terms of CED, obtainable with the use of cellulose HMA, is 160,5 MJ (-5,8% in comparison with the standard HMA), while the use of ELT fiber HMA can lead to a saving of 857 MJ (-30,8%). Such savings can be explained considering that the reinforced HMAs have longer service lives, thus less quantities of bitumen and other resources are used during the considered period of 30 years (as reported in Table 1, 38,3 kg, 24,3 kg and 19,6 kg of bitumen are necessary for the standard, cellulose and ELT fiber HMAs, respectively).

Even if the obtained figures cannot be quantitatively confirmed by comparative studies with the same FU and mixture recipes, similar recent studies qualitatively confirm the present results (Santero et al., 2011a; Farina et al., 2017): bitumen production is by far the most critical phase in terms of life cycle energy demand, followed by HMA production and transport of materials that cause more or less the same impacts.

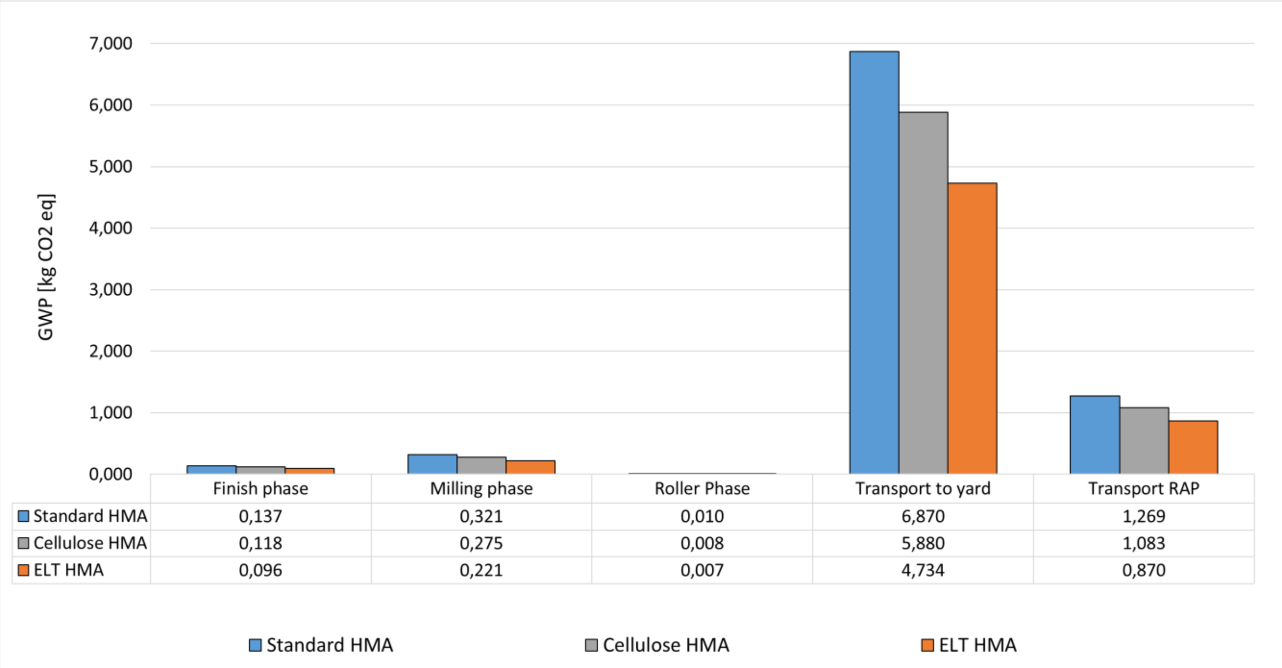
4.2 Global Warming Potential

The results calculated for the second considered indicator (i.e. GWP) are presented in the following figures. The results have been split between the different HMA production phases: raw material extraction and processing (



	Limestone 12/20	Limestone 8/16	Sand	Filler	Bitumen	Cellulose	ELT Fiber	Transport raw mat
Standard HMA	0,652	5,163	8,032	15,727	9,748			9,051
Cellulose HMA	0,562	4,431	6,807	13,575	8,365	2,640		7,488
ELT HMA	0,452	3,566	5,487	10,912	6,754		0,061	6,240

Figure 5), HMA production (Figure 6) and yard operation (



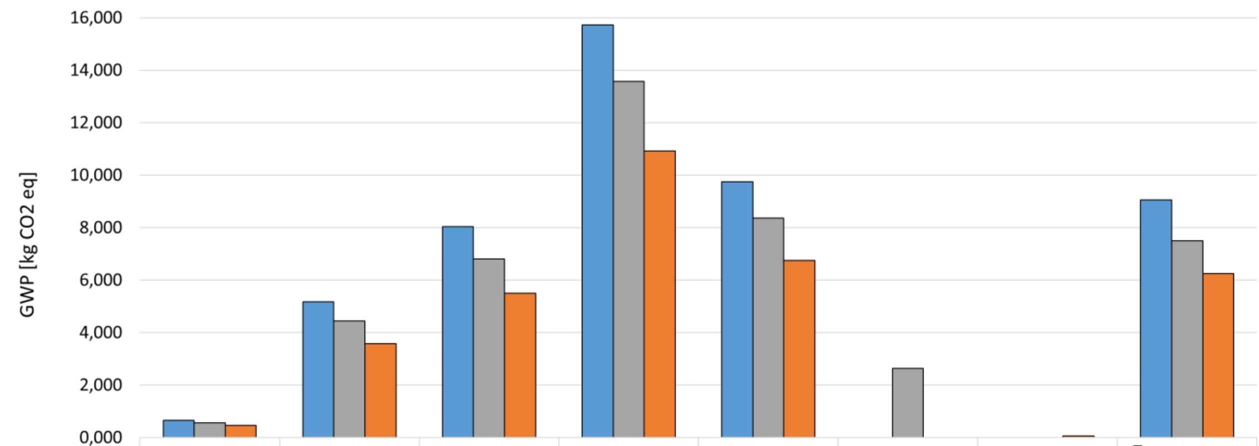
	Finish phase	Milling phase	Roller Phase	Transport to yard	Transport RAP
Standard HMA	0,137	0,321	0,010	6,870	1,269
Cellulose HMA	0,118	0,275	0,008	5,880	1,083
ELT HMA	0,096	0,221	0,007	4,734	0,870

Figure 7). Considering the entire life cycle of 30 years, the estimated total impacts in terms of GWP indicator for the three considered HMA mixtures are 62,6, 56,1 and 43,3 kgCO2eq, where the maximum value has been obtained for the standard HMA, while the most sustainable solution is the ELT fiber HMA. More specifically, the observed reductions in terms of GWP impact are -10,4 % by switching from standard HMA to cellulose HMA, and -30,8 % by switching from standard HMA to ELT fiber HMA.

The obtained results are in line with data derived from other relevant literature studies about the environmental performance of standard HMA mixtures. In particular, Miliutenko et al. (2013) calculated an impact of 57 kgCO_2eq per ton of HMA, Hammond and Jones (2010) estimated a value of 45 kgCO_2eq per ton, while the results presented by Giani et al. (2015) are in the range 52÷60,2 kgCO_2eq per ton. Such studies considered a life cycle of 30 years, but a different FU (production of

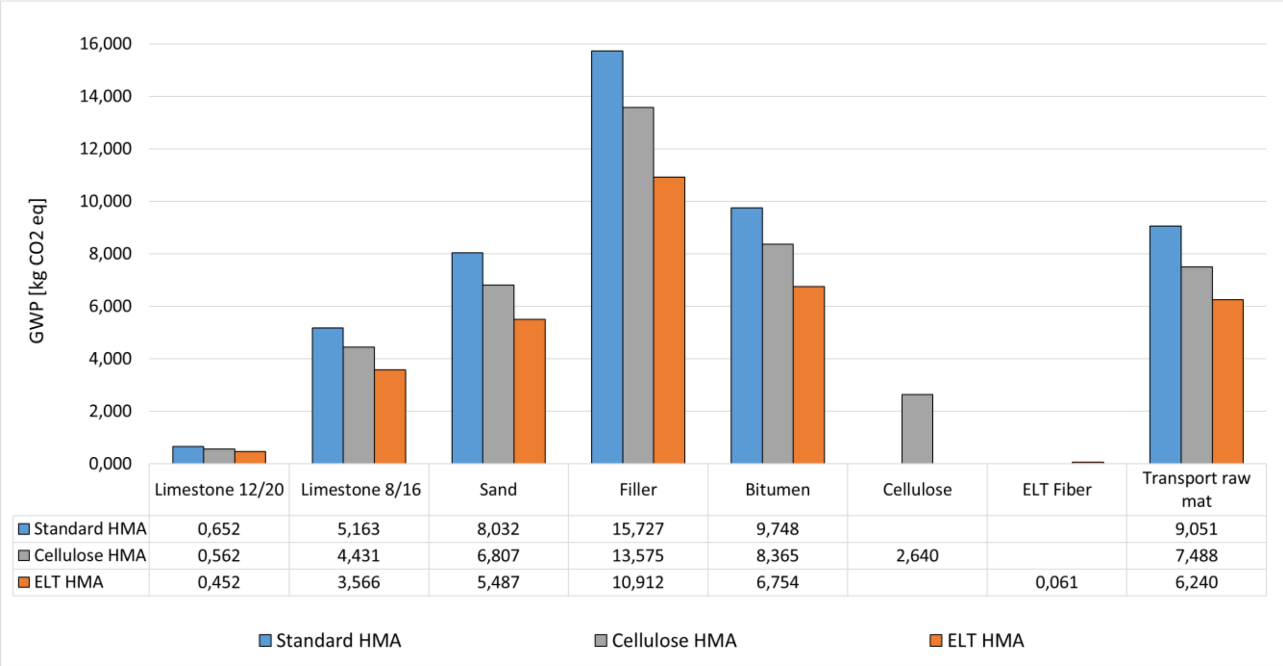
1 ton of HMA for the first two studies, 1 km of suburban road for the third one) and slightly different system boundaries and inventory data (e.g. quantity of RAP, emissions included in the LCI). Considering the FU chosen in the present study, the quantities of the needed HMA in the three considered scenarios are 1202,3 kg, 1023,5 kg and 823,6 kg for the standard, cellulose and ELT fiber HMAs, respectively. This difference of weight explains the difference in the obtained final results. Scaling the results obtained in the present study for the standard HMA to 1 ton, the estimated value is about 52 kg CO_2eq, fully in line with the results declared by Miliutenko et al. (2013) and Giani et al. (2015).

Going into more details,



	Limestone 12/20	Limestone 8/16	Sand	Filler	Bitumen	Cellulose	ELT Fiber	Transport raw mat
Standard HMA	0,652	5,163	8,032	15,727	9,748			9,051
Cellulose HMA	0,562	4,431	6,807	13,575	8,365	2,640		7,488
ELT HMA	0,452	3,566	5,487	10,912	6,754		0,061	6,240

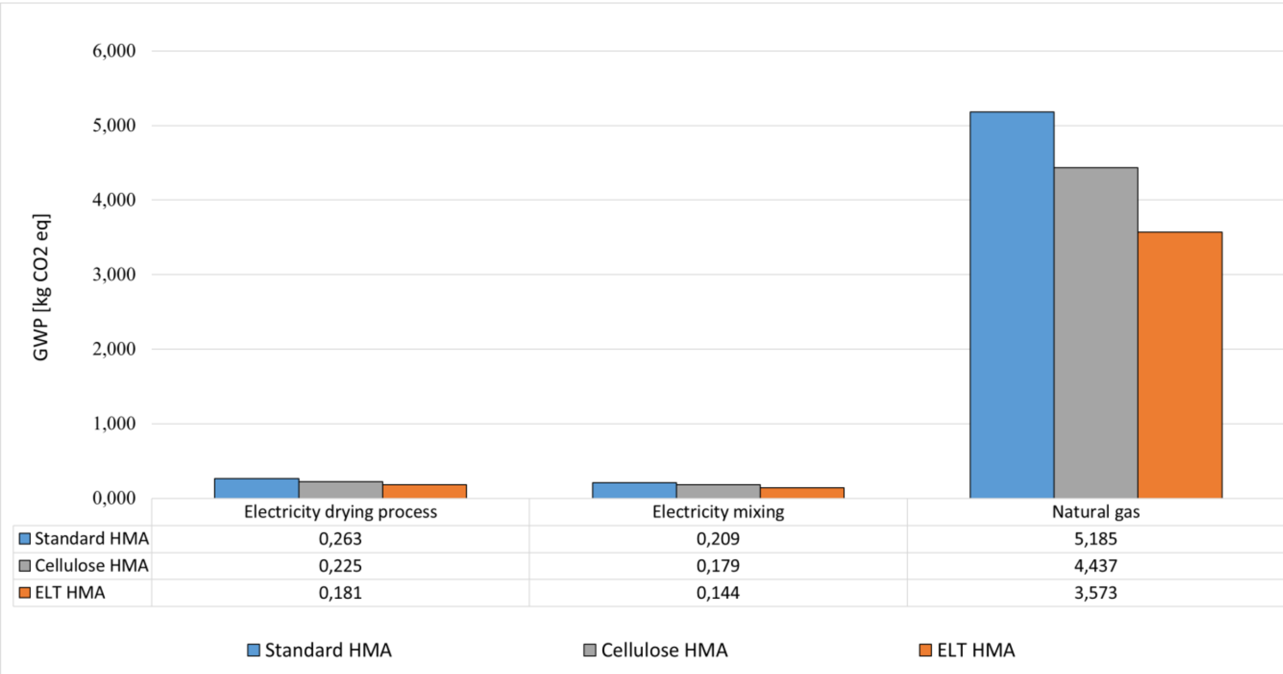
Figure 5 reports the results calculated for the raw materials extraction and processing phase, which is the most critical stage of the entire life cycle (about 77% of the total in all the three scenarios). In case of reinforced HMAs it is necessary to consider the impact of the reinforcement fiber. However, ELT fiber produces negligible emissions compared to the other raw materials (0,06 kgCO_2eq), while the impacts related to cellulose is 2,64 kgCO_2eq (6 % of the total raw materials impacts). Also the transport phase has a great importance in terms of CO_2 equivalent emissions, mainly due to the fact that transports of raw materials require the use of trucks with high tonnage and high consumption of diesel (about 0,5 l/km at full load).



	Limestone 12/20	Limestone 8/16	Sand	Filler	Bitumen	Cellulose	ELT Fiber	Transport raw mat
Standard HMA	0,652	5,163	8,032	15,727	9,748			9,051
Cellulose HMA	0,562	4,431	6,807	13,575	8,365	2,640		7,488
ELT HMA	0,452	3,566	5,487	10,912	6,754		0,061	6,240

Figure 5: LCIA in terms of GWP for raw materials extraction and processing

Figure 6 shows the GWP impacts for the HMA production phase, which consists in the drying and mixing of aggregates, bitumen and reinforcing fibers, where present. The use of fibers does not produce variations in the HMA production process, while the different impacts are due to the different quantities of HMAs needed in the period included in the FU (i.e. 30 years). As it is clear from the graph, the most impactful flow is the natural gas, needed to heat the mixtures of raw materials, which represents about the 90% of the total impact of the HMA production phase for all the three considered alternatives. The transition from HMA mixtures to warm mix asphalt mixtures could represent a best practice to reduce the natural gas consumption and thus the GWP impacts of the HMA production phase, as confirmed in other literature studies (D'Angelo et al., 2008; Vidal et al., 2013).



	Electricity drying process	Electricity mixing	Natural gas
Standard HMA	0,263	0,209	5,185
Cellulose HMA	0,225	0,179	4,437
ELT HMA	0,181	0,144	3,573

Figure 6: LCIA in terms of GWP for HMA production

Contributions of yard operations, shown in

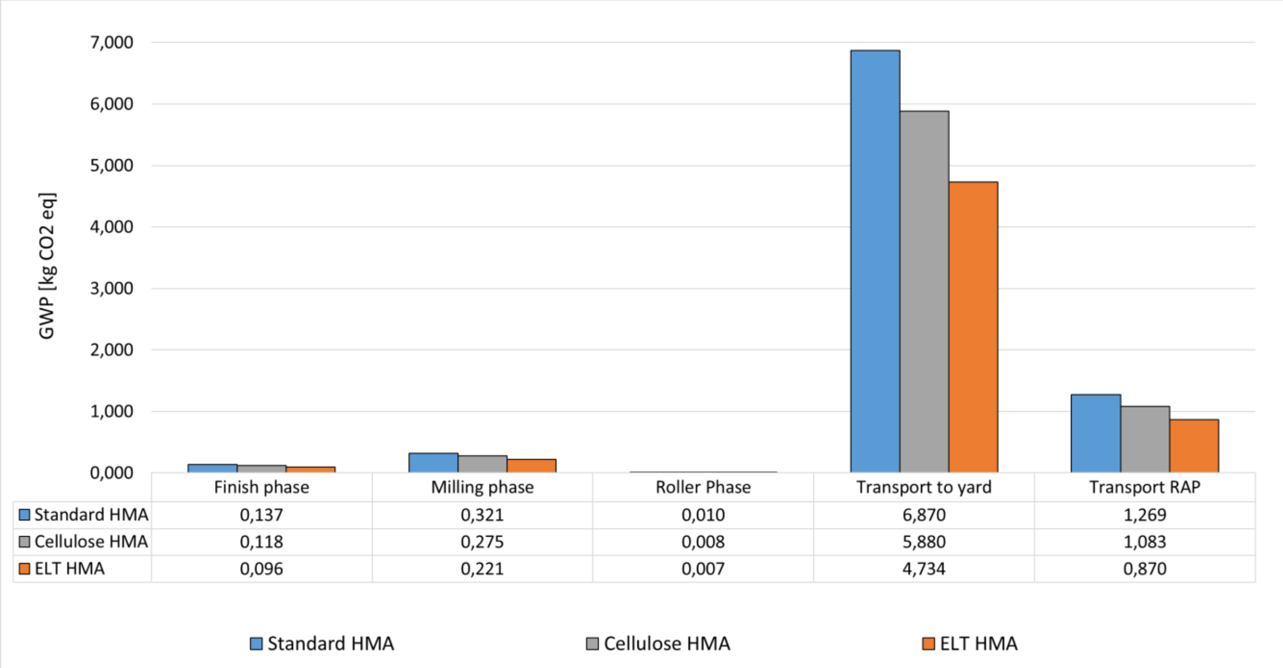


Figure 7, have almost negligible impacts. This result is fully in line with the state of the art (Tatari et al., 2012; Giani et al., 2015). However, the transports of HMA to yard and the transports of RAP heavily contribute to the global impacts of the yard operations (more than 90% of the total in all the three considered scenarios). Also in this case the differences among the three alternatives are due to the higher service life of the three layers in case of ELT fiber HMA.

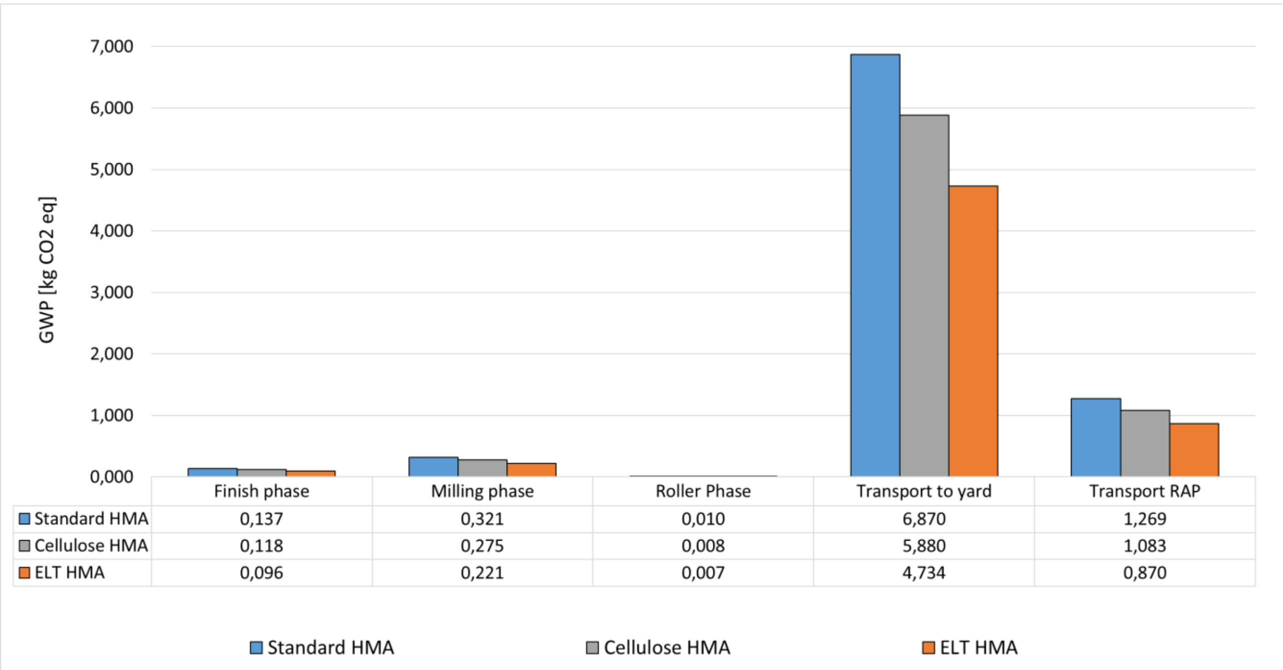
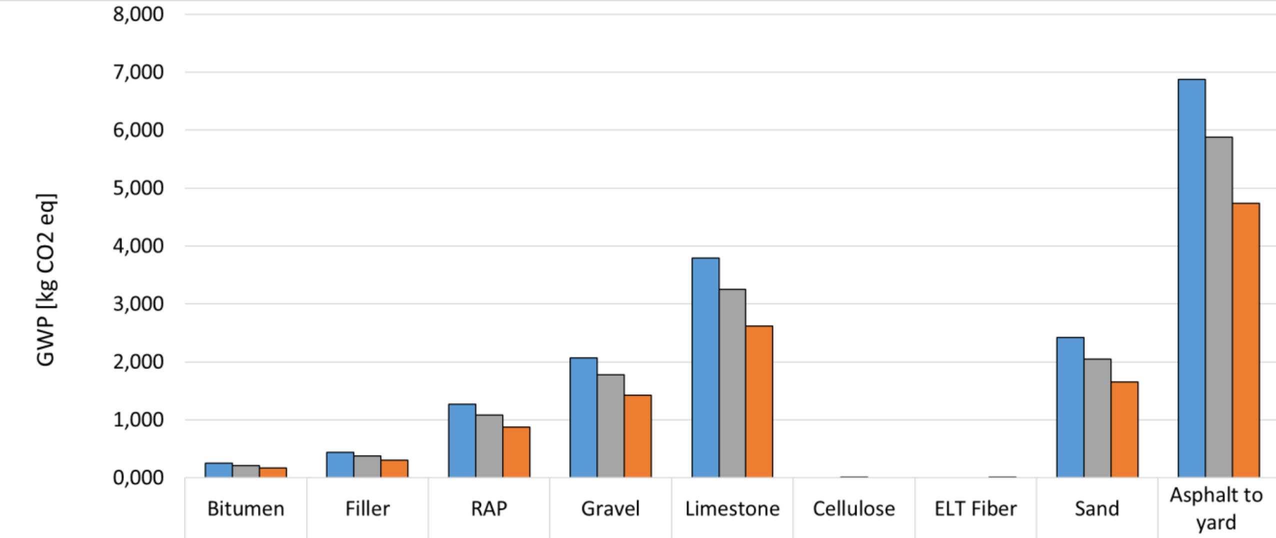


Figure 7: LCIA in terms of GWP for yard operation

Since the transport phases cause relevant impacts in terms of GWP in the HMA pavement life cycle (27,4 % for the standard HMA, 26 % for the cellulose HMA and 27,3 % for the ELT fiber HMA), a detailed investigation has been done for the transportation phases (Figure 8). As reported in the graph, about 40 % of the total transport GWP emissions are due to the transport of HMA to yard. An increase of the distance between the HMA production site and the yard would cause a sensible increase of the total environmental impacts of the three alternative HMA mixtures. However, this distance is not generally very high in order to prevent the excessive cooling of the HMA that would cause issues during the laying and finishing phases (e.g. increase of the laying time, difficulty to obtain a flat surface). For this reason, the distance considered in the LCI of the present study (i.e. 50 km) and, as a consequence the calculated environmental loads, can be considered representative of the real context where HMA production plants are geographically distributed. Concerning the transportation of the input raw materials, the high masses to transport cause high environmental impacts.

Considering the three scenarios under study, also for the transportation phase, the reinforced HMAs lead to a reduction of 14,4 % for the cellulose scenario and 28,3 % for the ELT fiber scenario, in comparison with the standard scenario. Once again these savings are due to the lower quantities of reinforced HMAs needed in the considered life cycle. The addition of cellulose or ELT fiber does not produce any sensible increase in the total impact (in both cases the needed quantity is very low, about 0,3% of the total mass as reported in Table 2).



	Bitumen	Filler	RAP	Gravel	Limestone	Cellulose	ELT Fiber	Sand	Asphalt to yard
Standard HMA	0,248	0,435	1,269	2,064	3,795			2,417	6,870
Cellulouse HMA	0,212	0,376	1,083	1,777	3,257	0,002		2,048	5,880
ELT HMA	0,172	0,302	0,870	1,428	2,621		0,002	1,651	4,734

Standard HMA Cellulouse HMA ELT HMA

Figure 8: LCIA in terms of GWP for the transportation phase

4.3 ReCiPe Midpoint and Endpoint

Concerning the ReCiPe method, both the midpoint (with the Hierarchist set of weights) and endpoint levels have been used. Characterized results obtained for all the 18 midpoint impact categories are shown in Table 6. Moreover, Figure 9 reports a “normalized” comparison among the three considered scenarios. The applied normalization has been made by dividing each total value by the maximum value obtained in each impact category. In this way, for each category, the most impactful scenario has an impact of 100%.

Analyzing the obtained results, it is possible to univocally establish that the best scenario from the environmental point of view is the ELT fiber HMA. However, depending on the chosen impact category, the rank of the three scenarios changes. In particular, for the Agricultural land occupation, Freshwater ecotoxicity, Freshwater eutrophication, Marine eutrophication and Terrestrial ecotoxicity impact categories the worst scenario is the cellulose HMA, while for the other ones is the standard HMA.

Table 6: LCIA in terms of characterized ReCiPe Midpoint H.

Impact Category	Standard HMA	Cellulose HMA	ELT Fiber HMA
Agricultural land occupation [m2a]	5,26E+00	8,62E+00	3,63E+00
Climate change [kg CO2-Equiv.]	6,26E+01	5,61E+01	4,33E+01
Fossil depletion [kg oil eq]	5,38E+01	4,70E+01	3,72E+01
Freshwater ecotoxicity [kg 1,4-DB eq]	2,26E-02	2,36E-02	1,56E-02
Freshwater eutrophication [kg P eq]	1,89E-04	2,29E-04	1,31E-04
Human toxicity [kg 1,4-DB eq]	2,45E+00	2,16E+00	1,70E+00
Ionising radiation [kg U235 eq]	1,42E+01	1,24E+01	9,81E+00
Marine ecotoxicity [kg 1,4-DB eq]	3,10E-02	2,71E-02	2,15E-02
Marine eutrophication [kg N-Equiv.]	1,11E-02	1,26E-02	7,74E-03
Metal depletion [kg Fe eq]	2,52E-01	2,19E-01	1,74E-01
Natural land transformation [m2]	4,27E-04	3,67E-04	2,96E-04
Ozone depletion [kg CFC-11 eq]	8,39E-10	7,99E-10	5,81E-10
Particulate matter formation [kg PM10 eq]	5,59E-02	5,00E-02	3,87E-02
Photochemical oxidant formation [kg NMVOC]	1,71E-01	1,54E-01	1,19E-01
Terrestrial acidification [kg SO2 eq]	1,53E-01	1,37E-01	1,06E-01
Terrestrial ecotoxicity [kg 1,4-DB eq]	6,32E-04	6,42E-04	4,37E-04
Urban land occupation [m2a]	2,09E-02	1,81E-02	1,45E-02
Water depletion [m3]	1,84E+02	1,59E+02	1,27E+02

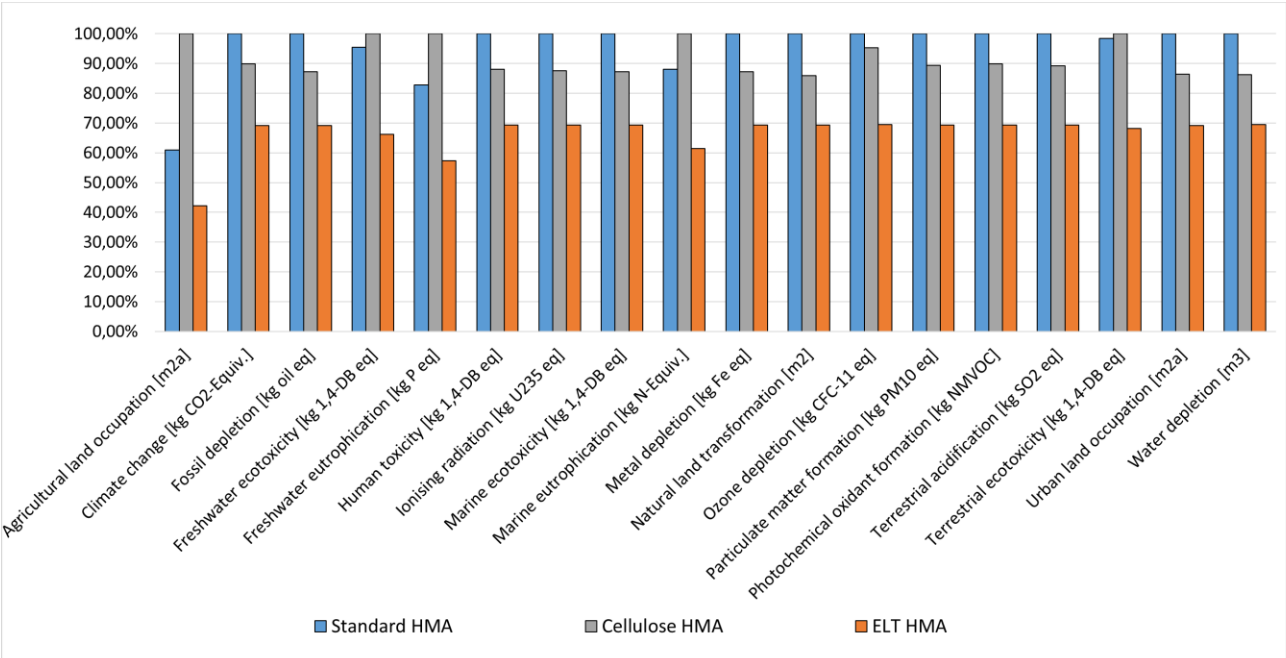


Figure 9: LCIA in terms of characterized ReCiPe Midpoint H (normalization applied)

In order to better investigate the most relevant causes of impacts for each category, Figure 10 shows the split of the normalized contributions at the midpoint level. In general, filler, bitumen and transports (yellow, blue and light blue bars in Figure 10, respectively) are the most impactful flows for almost all the impact categories and all the three scenarios. This result confirms the outcomes of the GWP and CED analyses. More in detail, Ecotoxicity is associated to the emissions of heavy metals and hydrocarbons and their adverse effect on the environment and organisms, including terrestrial, marine, freshwater and human environments and all the organisms at risk from chemical exposures. As highlighted in Figure 10 bitumen production affects significantly the marine and human toxicity assessment, in particular through the emission of polycyclic aromatic hydrocarbons (Fustinoni et al., 2010). Therefore, the reduction of the HMA service life and, as a consequence, the increasing of the needed bitumen quantity, potentially leads to the worsening of the environmental performance in these specific impact categories.

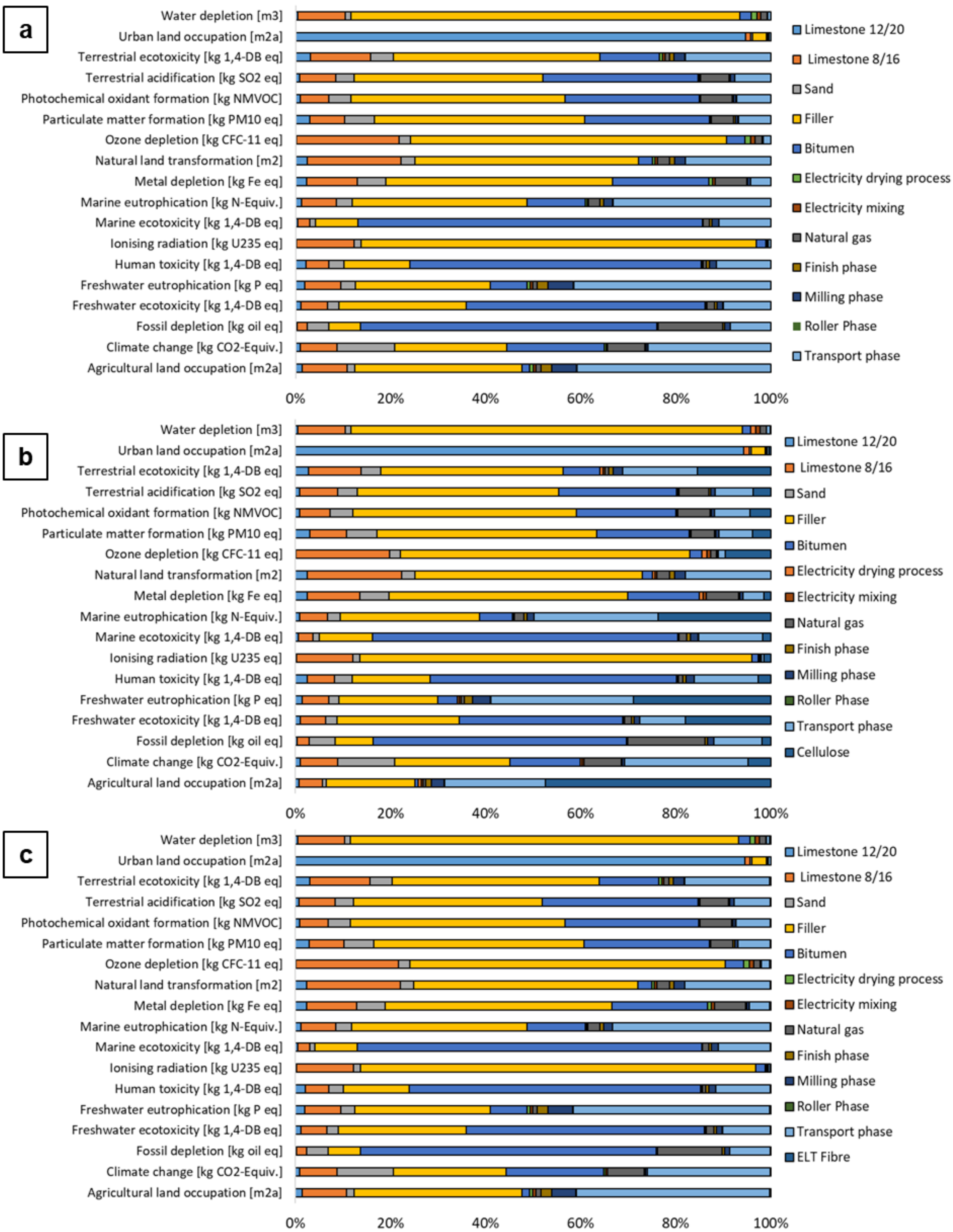


Figure 10: Relative contributions of different life cycle phases for the three scenarios. a) standard HMA, b) cellulose HMA, c) ELT fiber HMA.

Comparing the standard and the cellulose HMA, a non-negligible contribution due to the cellulose material (dark blue bar in Figure 10b) can be observed in those impact categories for which the cellulose HMA resulted the worst scenario. Despite the increase in service life of the cellulose HMA due to the use of a reinforcement (+15-20% for each layer in comparison with the standard HMA, as reported in Table 5), and the use of limited quantities of cellulose (only 3 kg in 30 years), the impact of the additional raw material strongly contributes to the increasing of the overall environmental load of the cellulose HMA pavement. The contribution of the cellulose is particularly relevant in case of the Agricultural land occupation impact category where its value is more than 47% of the total. This high impact can be explained by considering that the cellulose is produced by the chemical processing of lignin which is derived from trees.

Considering that the results obtained for the different midpoint indicators are not homogeneous, an analysis at the endpoint level has been conducted. Firstly, the characterized endpoints have been calculated, obtaining the results in terms of three damage categories (**Errore. L'origine riferimento non è stata trovata.**). Then, the final single score, after normalization and weighing, allowed to compare the results for the three scenarios in terms of a univocal indicator (Figure 11 and

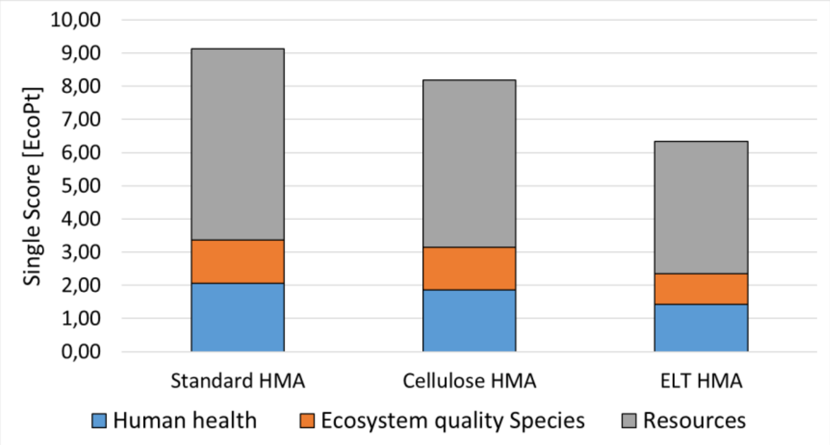


Figure 12).

The split of contributions (Figure 11) confirms the results obtained with the other environmental indicators: raw materials (in particular bitumen), natural gas consumed during the HMA production phase, and transports are the most impactful flows.

For all the three scenarios, the damage category that mainly contributes to the total single score is Resources, followed by Human Health and Ecosystem quality (

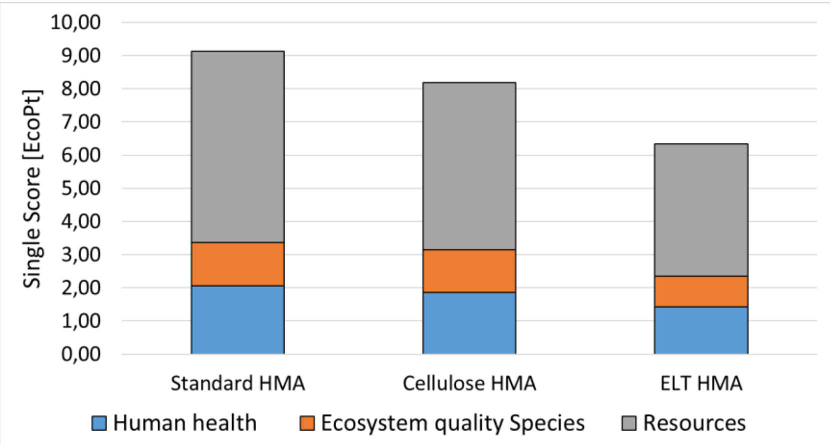
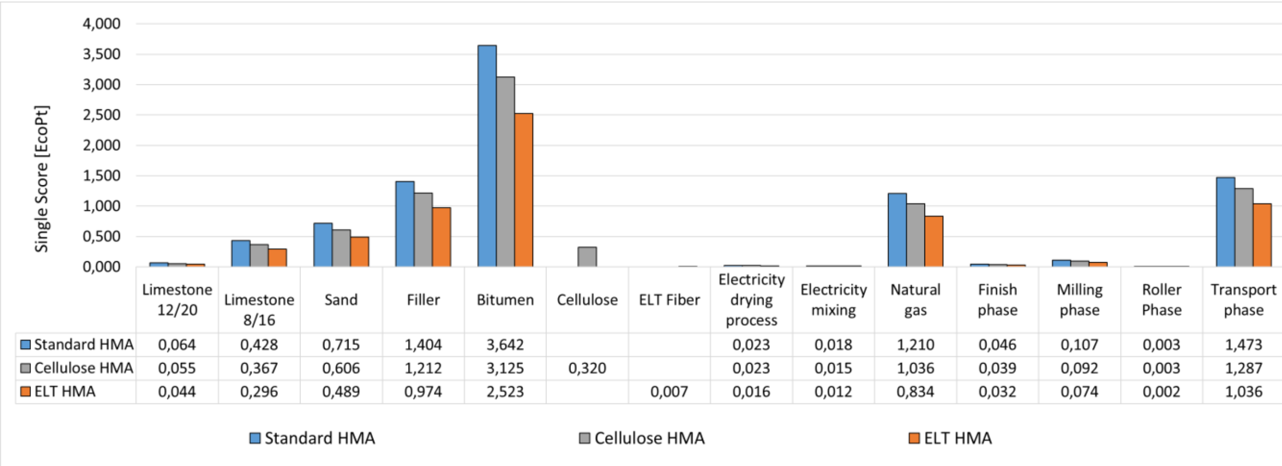


Figure 12). This result is in line with the outcomes of the CED and GWP analyses and can be explained by considering that the processes of HMA production and laying are connected with a high consumption of fossil resources (e.g. diesel for machines, fossils for the generation of electricity, natural gas, oil for the production of bitumen, fossil raw materials). A reduction of the quantity of

needed virgin materials (as in the case of ELT fiber reinforced HMA) allows minimizing the most relevant contribution, leading to an improvement of the HMA environmental performance.

Summarizing, moving from the standard HMA to the ELT fiber HMA, the following savings can be obtained (**Errore. L'origine riferimento non è stata trovata.**): about 0,32 DALY in terms of human health, 1,79 species.yr in terms of ecosystem quality species and 2,74 $ in terms of resources. The cellulose HMA, instead, allows reducing the impacts in terms of the three endpoint damage categories of about 0,1 DALY, 0,11 species.yr and 0,15 $ in comparison with the standard HMA.



	Limestone 12/20	Limestone 8/16	Sand	Filler	Bitumen	Cellulose	ELT Fiber	Electricity drying process	Electricity mixing	Natural gas	Finish phase	Milling phase	Roller Phase	Transport phase
Standard HMA	0,064	0,428	0,715	1,404	3,642			0,023	0,018	1,210	0,046	0,107	0,003	1,473
Cellulose HMA	0,055	0,367	0,606	1,212	3,125	0,320		0,023	0,015	1,036	0,039	0,092	0,003	1,287
ELT HMA	0,044	0,296	0,489	0,974	2,523		0,007	0,016	0,012	0,834	0,032	0,074	0,002	1,036

Figure 11: Split of the contribution for the ReCiPe Single score.

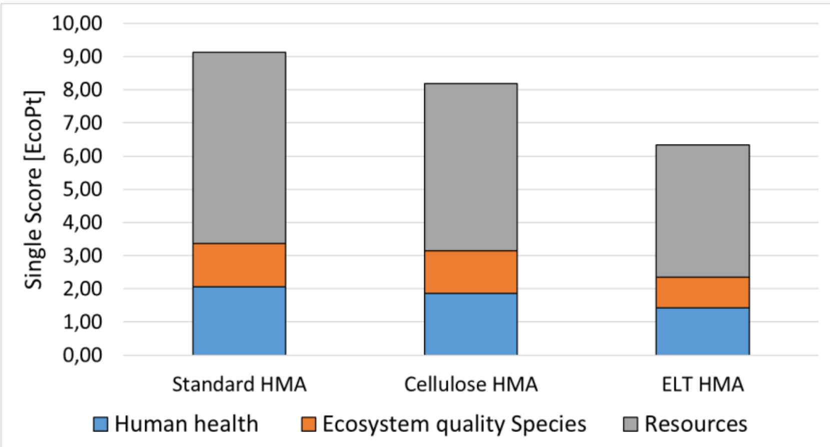


Figure 12: LCIA in terms of ReCiPe Single score.

Table 7: LCIA in terms of characterized ReCiPe Endpoint H.

Damage Category	Standard HMA	Cellulose HMA	ELT Fiber HMA
Human health [DALY]	1,04E-04	9,41E-05	7,23E-05
Ecosystem quality Species·[species.yr]	5,91E-07	5,80E-07	4,12E-07
Resources [$]	8,90E+00	7,75E+00	6,16E+00

5. Conclusions

Pavements and climate change are closely linked. The increase of the global population and the rapid urbanization will continue to place increased demands for transportation infrastructure requiring additional pavement construction. The present study aims to understand and evaluate the impacts of three different typologies of HMA used for road pavement construction: standard, cellulose-reinforced and ELT fiber-reinforced considering the different performances and service lives.

The experimental test results showed that the addition of fibers (natural or ELT) contributes to increasing bitumen drain down in porous asphalt mixtures. The presence of small particles of rubber in the ELT fibers reacts with the oily component of the bitumen, increasing the drainage effect of the asphalt compared to cellulose fiber. Furthermore, the use of ELT fibers as reinforcement, leads to a significant increase of the fatigue resistance of the HMA. As a consequence, the service life of ELT reinforced HMA is considerably major than the standard and cellulose HMA.

The presented life cycle assessment study includes the main phases related to HMA production and laying: raw material extraction, mixture production, transportation and road pavement construction. The obtained results show that extraction and production of virgin materials contribute with the highest impacts in the life cycle (up to 78 % in terms of GWP), mainly due to the use of bitumen and other fossil resources.

The main benefit related to the use of ELT fiber reinforced HMA is the increase of service life, which consequently leads to a decreasing of the needed quantities of aggregates, HMA to transport to the yard and resources (e.g. electric energy) consumed during the HMA production, in a life cycle perspective (30 years according to the FU considered in the present study). All these savings positively impact the life cycle environmental profile of the ELT fiber reinforced HMA in comparison with the standard and cellulose HMAs. Adopting a cellulose reinforced HMA, the environmental impacts are reduced of 5,8 %, 10,4 % and 10,4 % in comparison with standard HMA, considering the CED, GWP and ReCiPe Endpoint Single Score indicators, respectively. Switching to ELT fiber reinforced HMA the benefits are much greater: -30,8 % in terms of both CED and GWP, and -30,6 % in terms of ReCiPe Endpoint Single Score, in comparison with standard HMA.

Even if this study is based on a particular case it can be considered representative for the purpose of comparing the environmental performance of standard and reinforced HMA mixtures, since the most important phases, flows and processes related to the HMA production and laying have been considered. The use of measured data about the different HMA recipes and processes assured a sufficiently high reliability of results. However, different aspects should be better investigated to verify the contributions of additional aspects, as the emissions to air generated during the HMA production and laying, the influence of pavement use (e.g. extraordinary maintenance) and EoL (e.g. differences in pavement deconstruction due to reinforcements), etc. Given the high impacts generated by the transports (about 10 % of the total in terms of CED, more than 25 % in terms of GWP and more than 15 % in terms of ReCiPe endpoint Single Score), also these phases should be deeply analyzed. A very interesting future work should be focused on performing a sensitivity analysis by varying the transportation distances for both the input raw materials and the HMAs, with the aim to understand the influence on the total impacts of the geographical locations of suppliers, HMA producers and construction sites.

Finally, this research work opens the way to extend the study to other materials and asphalt production technologies (e.g. other typologies of reinforcements, wet technologies, rubber devulcanization treatments), evaluating for instance the potential environmental benefits deriving from the use of rejuvenators (industrial or natural) when high RAP contents are used.

Acknowledgements

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